

An Optimal Energy Storage Operation Scheduling Algorithm for a Smart Home Considering Life Cost of Energy Storage System

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Abstract – This paper presents an optimal operation scheduling algorithm for a smart home with energy storage system, electric vehicle and distributed generation. The proposed algorithm provides the optimal charge and discharge schedule of the EV and the ESS. In minimizing the electricity costs of the smart home, it considers not only the cost of energy purchase from the grid but also the life cost of batteries. The life costs of batteries are calculated based on the relation between the depth of discharge and life time of battery. As the life time of battery depends on the charge and discharge pattern, optimal charge and discharge schedule should consider the life cost of batteries especially when there is more than one battery with different technical characteristics. The proposed algorithm can also be used for optimal selection of size and type of battery for a smart home.

Keywords: Depth of discharge, Energy storage system, Scheduling and life cost of battery

1. Introduction

There have been many on-going studies about the smart systems. There are more of these studies as the propagation of components for the smart systems, such as the smart phone, smart home, and smart meter. The power system is one of the most active fields where these smart components are being integrated. Especially, the efficient integration and operation of energy storage systems (ESS) and electric vehicles (EV) in a power system is a significant topic in power system related studies.

Depending on the political or economic situation, electricity industry and electricity tariff structure is different. Electricity tariff systems can be largely categorized into a fixed tariff system and dynamic tariff system. In the dynamic tariff system, homes with smart meter and a battery can make an arbitrage taking advantage of the price changes and reduce the total electricity cost at a household. At a smart home, a parked EV could work as the battery and it can make an arbitrage through the charge/discharge following the price change.

In this paper, a study was made of the optimal control of distributed generation, energy storage system, and EV's battery to minimize electricity cost [1]. This study considers two types of batteries. The home energy storage system uses a lead-acid battery for household usage, whereas a lithium-ion battery is used for the EV. In this paper, the battery in the EV is used not only for a car itself but also for a home ESS. A lithium-ion battery is generally more economic for that of the EV [2].

The typical ESS for home can be equipped at indoors,

as there is no significant downside effect on its life at a moderate environmental temperature (e.g., room temperature). In [3], reflecting the big price difference between the lead-acid battery and the lithium-ion battery, the lead-acid battery is used for the home ESS. In this paper, on the contrary, both batteries are assumed to be used as the ESS for home. The lithium-ion battery and the lead-acid battery batteries have different characteristics in their life cycle and the depth of discharge (DoD) [4]. In this paper, for the minimum electricity cost, an optimal scheduling methodology is proposed for a home with both types of batteries having different characteristics. The electricity cost includes the life costs of these batteries that change depending on how they are used.

2. Optimal Scheduling of Energy Storage System

In this paper, an algorithm to minimize the cost of electricity in a household which has Photovoltaic panel (PV), Battery Energy Storage System (BESS) and EV is proposed. Especially it considers the characteristic of batteries that the DoD changes depending on how the batteries are used. Accordingly depending on the usage pattern of batteries, the life time of batteries changes and the life costs of batteries also change.

The EV's driving time, arrival time, the minimum energy before starting, and remaining energy after arriving are considered [5]. The real time electric power price, real time PV generation, and the electric power demand of a shiftable load are referred from [6]. The battery's state of energy (SOE), battery's total discharge power, and PV energy use and sell, shiftable load hours and the battery's DoD are decision variables [7, 8]. This optimal scheduling is carried out by use of mixed integer nonlinear programming

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(MINLP) and genetic algorithm of GAMS.

$$\forall t \geq 1 \quad (7)$$

2.1 Minimization of electricity cost

In a smart home, electric power can be bought from a grid or sold to a grid [9]. As a result, the objective function of the smart home is to minimize electricity cost as Eq. 1. The first term in the objective function is the cost the smart home has to pay to the grid for the usage of electricity from the grid, while the second term is the revenue the smart home collects from the grid.

$$\min TC = \sum_t \left(\frac{P_t^{grid}}{\Delta T} \cdot \lambda_t^{buy} - \frac{P_t^{sold}}{\Delta T} \cdot \lambda_t^{sell} \right) \quad (1)$$

Eq. 2 represents power balance at the smart home. The left side of Eq. 2 is the injection energy to the smart home, which consists of grid power, PV generation, and EV/ESS discharging. The right side is the consumption energy by the smart home that is consumed by non-smart home appliances, EV/ESS charging and smart appliances. The charging efficiencies of lead-acid battery ESS in the home and lithium-ion battery in the EV are considered in determining the power consumption.

$$P_t^{grid} + P_t^{PV,used} + P_t^{EV,used} + P_t^{ESS,used} = P_t^{other} + \frac{P_t^{EV,ch}}{CE_{EV}} + \frac{P_t^{ESS,ch}}{CE_{ESS}} + \sum_m P_{t,m}^{shift}, \quad \forall t \quad (2)$$

The constraint related with lead-acid battery ESS discharge is Eq. 3. The power used and sold to the grid is assumed to be discharged from lead-acid battery ESS. Discharge efficiency of lead-acid battery ESS is considered in this constraint.

$$P_t^{ESS,used} + P_t^{ESS,sold} = P_t^{ESS,dis} * DE_{ESS}, \quad \forall t \quad (3)$$

The constraint of the maximum charging and discharging rates of lead-acid battery ESS are defined by Eq. 4 and Eq. 5.

$$P_t^{ESS,ch} \leq CR_{ESS} * u_t^{ESS}, \quad \forall t \quad (4)$$

$$P_t^{ESS,dis} \leq DR_{ESS} * (1 - u_t^{ESS}), \quad \forall t \quad (5)$$

The initial state-of-energy of the ESS is shown in Eq. 6. If it is not the initial time, the state-of-energy of the ESS is defined as Eq. 7 where the second and the third terms are charged and discharged power at present time t .

$$SOE_t^{ESS} = SOE_t^{ESS,ini}, \quad \text{if } t = 1 \quad (6)$$

$$SOE_t^{ESS} = SOE_{t-1}^{ESS} + \frac{P_t^{ESS,ch}}{\Delta T} - \frac{P_t^{ESS,dis}}{\Delta T}$$

The maximum and minimum state-of-energy of the ESS are shown in Eq. 8 and Eq. 9.

$$SOE_t^{ESS} \leq SOE_t^{ESS,max}, \quad \forall t \quad (8)$$

$$SOE_t^{ESS} \geq SOE_t^{ESS,min}, \quad \forall t \quad (9)$$

The lithium-ion battery in the EV can be used as an ESS in the smart home. Thus, the operation constraints of EV and BESS are basically same as those shown in Eq. 3-10 is basically the same one with Eq. 3. The sum of EV used energy, or discharge energy, and EV sold energy is same as the EV discharged energy considering efficiency [10]. Eq. 11-14 are the same ones with Eq. 4-7 which are constraints of charge / discharge rate and state of energy. The maximum and minimum state-of-energy of the lithium-ion battery in the EV is shown in Eq. 15 and Eq. 16.

$$P_t^{EV,used} + P_t^{EV,sold} = P_t^{EV,dis} * DE_{EV} \quad \forall t \in [T^a, T^d] \quad (10)$$

$$P_t^{EV,ch} \leq CR_{EV} * u_t^{EV}, \quad \forall t \in [T^a, T^d] \quad (11)$$

$$P_t^{EV,dis} \leq DR_{EV} * (1 - u_t^{EV}), \quad \forall t \in [T^a, T^d] \quad (12)$$

$$SOE_t^{ESS} = SOE_t^{ESS,ini}, \quad \text{if } t = T^a \quad (13)$$

$$SOE_t^{ESS} = SOE_{t-1}^{ESS} + \frac{P_t^{ESS,ch}}{\Delta T} - \frac{P_t^{ESS,dis}}{\Delta T} \quad \forall t \in [T^a, T^d] \quad (14)$$

$$SOE_t^{EV} \leq SOE_t^{EV,max}, \quad \forall t \in [T^a, T^d] \quad (15)$$

$$SOE_t^{EV} \geq SOE_t^{EV,min}, \quad \forall t \in [T^a, T^d] \quad (16)$$

The EV has time of use constraints where arrive/drive schedule should be considered. Eq. 17 represents that the EV should be maintained at a certain level of energy before the driving time. The variation of the EV battery is 0 when the EV is not parked at the smart home as in Eq. 18.

$$SOE_t^{EV} = SOE_t^{EV,drive}, \quad \forall t \in [T^a, T^d] \quad (17)$$

$$SOE_t^{EV} = P_t^{EV,used} = P_t^{EV,sold} = P_t^{EV,dis} = P_t^{EV,ch} = 0, \quad \forall t \notin [T^a, T^d] \quad (18)$$

The distributed generation in the smart home consists of small generation, such as photovoltaic (PV), fuel cell and so on. In this paper, the distributed generation is assumed as a PV.

$$P_t^{PV,used} + P_t^{PV,sold} = P_t^{PV,pro} \quad (19)$$

In this paper, the PV is assumed to be connected to the grid. All the energy that the PV produces is supplied to the home appliances or sold to a grid, as in Eq. 19.

$$P_t^{sold} = P_t^{PV,sold} + P_t^{ESS,sold} + P_t^{EV,used}, \quad \forall t \quad (20)$$

The constraint of energy sold by the smart home is shown in Eq. 20. In this paper, the energy of PV, ESS, and EV can be sold to the grid.

2.2 Life cost of energy storage system

The C-rate or charge rate is the charging and discharging speed of a battery [11], [12]. We assumed that the charging and discharging speed are the same.

$$C-rate_t^{ESS} = \frac{P_t^{ESS,dis}}{SOE_t^{ESS,max}} \quad (21)$$

$$C-rate_t^{EV} = \frac{P_t^{EV,dis}}{SOE_t^{EV,max}} \quad (22)$$

Eq. 23 and Eq. 24 are the definition of DoD.

$$DoD_t^{ESS} = C-rate_t^{ESS} * \Delta T \quad (23)$$

$$DoD_t^{EV} = C-rate_t^{EV} * \Delta T \quad (24)$$

Using the C-rate, the relationship between DoD (Eq. 23-24) and discharge power (Eq. 21-22) can be calculated as in Eq. 25-26, where the value of DoD ranges from 0 to 1

$$DoD_t^{ESS} = \frac{P_t^{ESS,dis} * \Delta T}{SOE_t^{ESS,max}} \quad (25)$$

$$DoD_t^{EV} = \frac{P_t^{EV,dis} * \Delta T}{SOE_t^{EV,max}} \quad (26)$$

$$0 \leq DoD_t^{ESS} \leq 1 \quad (27)$$

$$0 \leq DoD_t^{EV} \leq 1 \quad (28)$$

The relationship between the cycle life and DoD for the lead acid battery can be expressed by a linear function as shown in Eq. 29 [13]. The relationship between the cycle life and DoD for the lithium-ion battery can be expressed by a non-linear function shown in Eq. 30 [13].

$$L_t^{ESS} = -4775 DoD_t^{ESS} + 4955 \quad (29)$$

$$L_t^{EV} = 694 DoD_t^{EV-0.795} \quad (30)$$

Generally, in the most researches, the DoD of battery is usually set by 80% and the abrasion cost becomes always constant [1]. However, in this paper, in order to change the DoD depending on the discharge quantity, formulas are

applied as follows. The life cost of energy storage system can be described as in Eq. 31 and Eq. 32. The total life cost of battery is the purchasing cost divided by wear cost of discharge. The battery life changes with DoD. Therefore, the wear cost is variable when the battery discharges. Finally, the life cost is the value that the purchase cost for battery is divided by life cycle of battery considering the DoD.

$$Cost_t^{ESS} = \frac{\alpha_{ESS}}{L_t^{ESS}} \quad (31)$$

$$Cost_t^{EV} = \frac{\alpha_{EV}}{L_t^{EV}} \quad (32)$$

It is assumed that if the battery is discharging, then the life of the battery is decreased and the life remains unchanged when the battery is not discharging. Therefore, the objective function of the energy storage system scheduling, considering the life cost of batteries, is changed into Eq. 33.

$$\min TC = \sum_t \left(\frac{P_t^{grid}}{\Delta T} \times \lambda_t^{buy} - \frac{P_t^{sold}}{\Delta T} \times \lambda_t^{sell} + \frac{\alpha_{ESS}}{L_t^{ESS}} * (1 - u_t^{ESS}) + \frac{\alpha_{EV}}{L_t^{EV}} * (1 - u_t^{EV}) \right) \quad (33)$$

3. Case Syudy

In this paper, to calculate the smart home's minimum electricity cost, Korean System Marginal Price (SMP) in July 2011 is applied. At the smart home, the energy and operation hour of general appliances and smart appliances are the same as those in [6, 2] and [14]. And the PV's one-day energy production is also same as that in [6]. The features of ESS and EV and the parameter are presented in the Table 1, with reference to [6] and [15].

In this paper, 7 cases are studied. The simulation days are set as 30 days. In all the cases, the PV is assumed to supply energy to home appliances and to be able to sell electricity to the system. In case 1, 2 and 3, the effect of the abrasion cost is analyzed and in case 4, 5, 6 and 7,

Table 1. The parameters of ESS and EV

	ESS	EV	EV Schedule	
Charging efficiency	0.95	0.95	Drive	8:00
Discharging efficiency	0.95	0.95		
Maximum charging rate	2kW	13.2kW	SOE before driving	14kWh
Minimum SOE	0.6 kWh	2.8kWh	Arrive	17:00
Maximum SOE	3 kWh	16 kWh		
Initial SOE	3 kWh	14 kWh	SOE at arrival	10kWh
Purchase cost	80\$/ kWh	315\$/ kWh		

Table 2. Assumptions of case study

	PV	ESS & EV	Wear Cost
Case 1	●	○	○
Case 2	●	●	○
Case 3	●	●	●
Case 4		80% installation cost of ESS form case 3	
Case 5		60% installation cost of ESS form case 3	
Case 6		20% installation cost of EV form case 3	
Case 7		10% installation cost of EV form case 3	

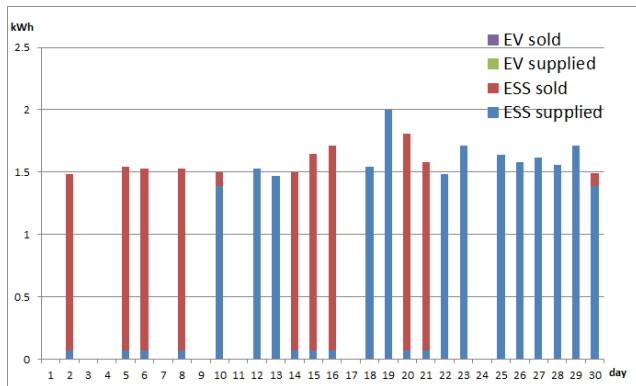


Fig. 1. Discharging schedule of ESS and EV (Case 3)

sensitivity studies are made by changing the price of ESS and EV while PV, ESS and abrasion cost are all considered.

The assumptions of case 1~7 are presented in Table 2. In case 1, the ESS is not installed and EV is just applied as a load (i.e., the EV only performs charging). Thus, the revenue is earned solely by the PV's selling electricity. In case 2, the installation cost and wear cost are not considered for the ESS and EV. Thus, the arbitrage through charge/discharge is achieved most briskly. Case 3 is similar to case 2 but the installation cost and wear cost are considered. Cost sensitivity analysis are done based on case 3, decreasing the ESS and EV installation cost.

The simulation result of ESS and EV are shown in Fig. 1. ESS and EV discharging are classified as two parts by usage such as the energy sold to grid and supplied to home. Case 3 is simulated for a month. During these days, EV battery does not discharge to sell to the grid and to supply to home to minimize wear cost while ESS discharges to sell to the grid and to supply to home to minimize total cost. This result shows that the proposed algorithm works properly, in other words, the usage of high cost EV lithium-ion battery is lessened by the usage of low cost ESS lead acid battery.

In Fig. 2, the purchasing costs of the 7 cases were compared. In the case 2, since the price of ESS and EV is 0 and there is no wear cost, it has the highest purchasing cost. As ESS and EV costs are decreasing from case 3 to case 7, case 7's graph is almost same as case 2 with decreasing installation costs.

In Fig. 3, the sales revenues of the 7 cases are compared. In the case 2, since there's no installation cost and wear

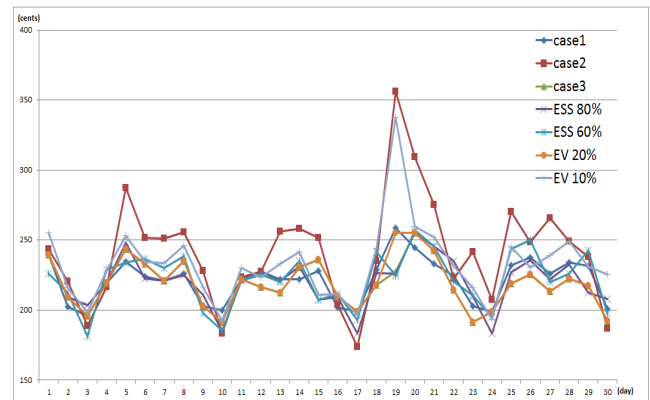


Fig. 2. Purchase cost of case1-3 and cost sensitivity

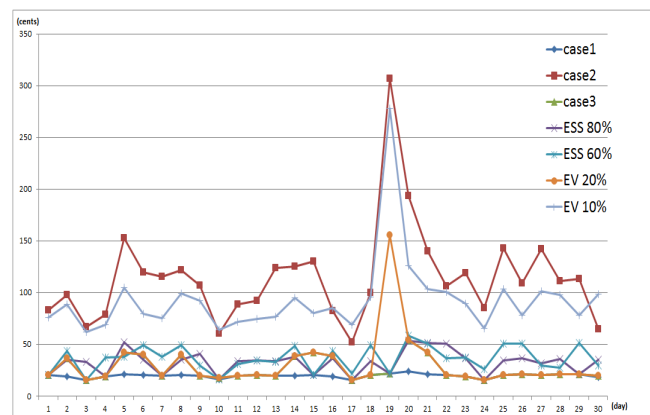


Fig. 3. Sales revenue of case 1-3 and cost sensitivity

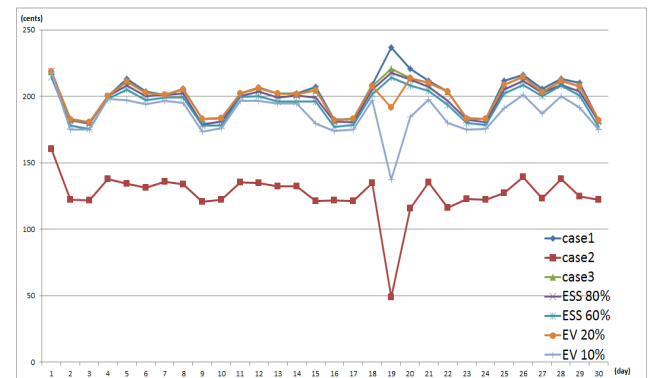


Fig. 4. Total cost of case 1-3 and cost sensitivity

cost of ESS and EV, it performs charge/discharge most briskly. Therefore, it has the highest sales revenue, as in Fig. 2. In the case 1, since there's no arbitrage between the ESS and EV, so it has fixed sales revenue by PV. In the case 3 and the analyzation of cost sensitivity (case 4-7), with decreasing the installation cost of ESS and EV, it is able to say that charge/discharge proceeds in a similar way to that in the case 2.

In Fig. 4, the total costs of the 7 cases are compared. In case 2, which doesn't have an installation cost, it shows the

Table 3. Results of case study

Cases	Purchase cost (cents)	sales revenue (cents)	Wear cost (cents)	Total cost (cents)	Cost reduction (cents)
1	6641.3	597.2	-	6044.0	-
2	7227.1	3437.5	-	3789.6	2254.4
3	6554.2	788.7	234.1	5999.6	44.4
4 (80% installation cost of ESS)	6601.7	983.9	312.5	5930.4	113.6
5 (60% installation cost of ESS)	6658.8	1093.6	277.6	5842.8	201.2
6 (20% installation cost Of EV)	6581.8	922.4	311.0	5970.4	73.6
7 (10% installation cost of EV)	6974.2	2782.8	1410.5	5602.1	441.9

lowest cost by performing the arbitrage most briskly. In the case 1, since the ESS and EV don't perform the difference transaction through charge/discharge but only operates as a load, so it shows the highest total cost. In case 3 and ESS, the EV cost sensitivity analyzation (case 4-7), as the installation cost of the ESS and EV decreases gradually, the total costs shows similar pattern to that of case 2.

Table 3 is the summary of the results of each case. Purchasing cost, sales revenue, and total cost are calculated.

4. Conclusion

At the smart home one can supply the energy to home appliances and sell the energy to a system and save the electricity cost by using the energy storage system [16]. However, the installation cost for the energy storage system and life cost, that decreases whenever used, should be considered. Thus, before the installation of an energy storage system at a home, it is necessary to calculate the electricity cost in which the life cost of batteries is considered. The existing studies fixed the life of the energy storage system. However, since the life changes depending on the discharge amount of the energy storage system, there should be a consideration of the change of life depending on the change in the discharge amount and pattern.

In this paper, we performed a study about the optimum operation scheduling algorithm of a smart home which consists of the ESS, EV, distributed power, and smart electronic appliance. Furthermore, we minimized the electricity cost with the consideration of the abrasion cost of energy storage system by the change of the discharge rate following the changing SMP and electricity load. The optimization problem is solved by use of MINLP (Mixed Integer Non-Linear Programming) and genetic algorithm of the GAMS.

The proposed algorithm can also be applied in determining the optimal size and type of ESS for a home or a factory while the EVs are available as an auxiliary ESS. The future study may include the optimal operation of

dispatchable distributed generation such as fuel cell or micro turbine with ESS.

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Nomenclature

P_t^{grid}	Power supplied by the grid(kW)
P_t^{sold}	Total power injected to the grid(kW)
λ_t^{buy}	Price of energy bought from grid(cents/kW)
λ_t^{sell}	Price of energy sold back to the grid(cents/ kW)
ΔT	Number of time intervals in 1 h
$P_t^{\text{PV,used}}$	Power used to satisfy household load from the PV(kW)
$P_t^{\text{PV,sold}}$	Power injected to grid from the PV(kW)
$P_t^{\text{PV,pro}}$	Power produced by the PV(kW)
$P_t^{\text{EV,used}}$	Power used to satisfy household load from the EV(kW)
$P_t^{\text{EV,ch}}$	EV charging power(kW)

$P_t^{\text{EV,sold}}$	Power used to satisfy household load from the ESS(kW)
$P_t^{\text{EV,dis}}$	EV discharging power(kW)
$P_t^{\text{ESS,used}}$	Power used to satisfy household load from the ESS(kW)
$P_t^{\text{ESS,ch}}$	ESS charging power(kW)
$P_t^{\text{ESS,sold}}$	Power injected to grid from the ESS(kW)
$P_t^{\text{ESS,dis}}$	ESS discharging power(kW)
P_t^{other}	Household power demand(kW)
$P_{t,m}^{\text{shift}}$	Shiftable household power demand(kW)
$\text{SOE}_t^{\text{ESS}}$	State-of-energy of the ESS(kWh)
$\text{SOE}_{\text{ESS,max}}^{\text{ESS}}$	Maximum allowed state-of-energy of the ESS (kWh)
$\text{SOE}_{\text{ESS,min}}^{\text{ESS}}$	Minimum allowed state-of-energy of the ESS (kWh)
$\text{SOE}_t^{\text{ESS,ini}}$	Initial state-of-energy of the ESS(kWh)
SOE_t^{EV}	State-of-energy of the EV(kWh)
$\text{SOE}_{\text{EV,max}}^{\text{EV}}$	Maximum allowed state-of-energy of the EV (kWh)
$\text{SOE}_{\text{EV,min}}^{\text{EV}}$	Minimum allowed state-of-energy of the EV (kWh)
$\text{SOE}_t^{\text{EV,ini}}$	Initial state-of-energy of the EV(kWh)
$\text{SOE}_t^{\text{EV,drive}}$	Minimum state-of-energy of the EV before driving (kWh)
T^a	Time of EV arrived
T^d	Time of EV driving
CR_{ESS}	Charging rate of the ESS(kW per time interval)
DR_{ESS}	Discharging rate of the ESS(kW per time interval)
CE_{ESS}	Charging efficiency of the ESS
DE_{ESS}	Discharging efficiency of the ESS
CR_{EV}	Charging rate of the EV(kW per time interval)
DR_{EV}	Discharging rate of the EV(kW per time interval)
CE_{EV}	Charging efficiency of the EV
DE_{EV}	Discharging efficiency of the EV
u_t^{ESS}	Binary variable: 1 if ESS is charging during period t, 0 else
u_t^{EV}	Binary variable: 1 if EV is charging during period t, 0 else
$\text{C-rate}_t^{\text{ESS}}$	ESS discharge rate during period t(per unit time, ext. 60min=1, 15min=4)
$\text{C-rate}_t^{\text{EV}}$	ESS charge rate during period t(per unit time, ext. 60min=1, 15min=4)
$\text{DoD}_t^{\text{ESS}}$	DoD of ESS
DoD_t^{EV}	DoD of EV
L_t^{ESS}	Life cycle of ESS during period t
L_t^{EV}	Life cycle of EV during period t
$\text{Cost}_t^{\text{ESS}}$	Cost of ESS discharging
$\text{Cost}_t^{\text{EV}}$	Cost of EV discharging
α_{ESS}	Purchasing cost of ESS
α_{EV}	Purchasing cost of EV



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